LETTER OF NOTIFICATION

Lawrence Berkeley Laboratory
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NIGEL W.,T. QUINN, PhD, P.E>
EARTH SCIENCES DIVISION
PHONE: (510) 486 7056 FAX: (510) 486 7152

March 30, 1999.

Ms. Lydia Beiswanger, Chief Deputy
Merced County Board of Supervisors
2222 M Street
Merced, CA 95340.

Dear Ms. Beiswanger:

This letter is to inform you of our intent to submit a proposal to the CALFED Bay-Delta Program entitled "Real-Time Forecasting of Contaminant Loading from the Panoche/Silver Creek Watershed to the San Joaquin River". This a joint proposal with the Panoche/Silver Creek Coordinated Resource Management Committee, a grass-roots organization comprising local landowners, State, Federal and local agency personnel.

Accurate forecasting of flood flows will provide an early warning to the Grassland Area Farmers allowing more time to plan emergency response plans to these flooding events. Flooding of farm land during 1997 and 1998 overwhelmed the resources of the agricultural water districts in the Grasslands Basin to contain these flows. The effect of these flood flows on water quality in the San Joaquin River has not been quantified adequately to assess the impact on River assimilative capacity for selenium, boron and TDS. The monitoring associated with this project will help to improve this deficiency and will help to improve the accuracy of water quality forecasts made by the currently supported CALFED Real-Time Water Quality Management project on the San Joaquin River.

We believe that successful completion of this study will be of great benefit to landowners and water district personnel in the Grassland watershed of Merced County.

Sincerely,

Nigel W.T. Quinn

Nigel W.T. Quinn

Geological Scientist

PANOCHE WATER DISTRICT

52027 WEST ALTHEA, FIREBAUGH, CA 93622 • TELEPHONE (209) 364-6136 • FAX (209) 364-6122

April 7, 1999

Dr. Nigel W.T. Quinn
Lawrence Berkeley National Laboratory
1 Cyclotron Road, 70A-3317K
Berkeley, CA 94720

Subject: Panoche Water District Support for CALFED Grant Proposals

Dear Dr. Quinn:

The Panoche Water District has a long history of supporting innovative drainage reduction strategies on the west-side of the San Joaquin Valley. As a participant in the Grassland Bypass Project the water district has invested millions of dollars in the past 3 years to improve monitoring and increase control over subsurface tile drainage leaving the water district. Significant reductions in selenium loads contained in these discharges have been necessary to meet the strict selenium load limits imposed by the Project.

The CALFED proposal entitled "Real Time Forecasting of Contaminant Loading from the Panoche/Silver Creek Watershed to the San Joaquin River" that you are submitting cooperatively with the Panoche/Silver Creek Coordinated Resource Management is of great interest to the District. Rainfall-runoff from the Panoche/Silver Creek watershed caused flooding to farm land during 1997 and 1998 and overwhelmed the resources of the District to contain these flows. Accurate forecasting of flood flows will provide an early warning to the Grassland Area Farmers allowing more time to plan emergency response plans to these flooding events. Successful completion of this study will be of great benefit to landowners and water district personnel in the Grassland watershed.

Sincerely,

Dennis Falaschi

Dennis Falaschi
General Manager

California Natural Resource Foundation
1151 Kadota Avenue, Atwater, California 95301
Phone: (209) 358-9026 Cellular: (209) 761-2563 Fax: (209) 726-3881 Email: mark@elite.net

Saturday, March 20, 1999

Mr. Earle Cummings, Chairman
Water Quality Subcommittee
San Joaquin River Management Program
Department of Water Resources
3251 S Street, Sacramento, CA 95816

Subject: CNRF Support for CalFed Grant Proposals

Dear Mr. Cummings:

The California Natural Resources Foundation is a charitable non-profit charitable Foundation and supports a broad array of projects to benefit the preservation of productive natural systems. Recent projects we have supported or facilitated include wetland restoration at the Castle Land and Cattle Co. and mitigation banks in the Merced area and the Suisun Marsh. We are working with interested parties in Merced and other San Joaquin Valley cities to use constructed wetlands to improve the quality of discharges from municipal wastewater treatment plants.

We support your Subcommittee's grant proposals to CalFed, and have commitments from our board members to assist in your proposal. Our board includes members with skills in finance, habitat development, community relations, State and Federal Contract Management, and regulatory compliance. We have a cooperative agreement in place with the California Waterfowl Association for projects that require engineering of water management structures. We are very interested in your proposals:

1. To develop understanding and improved management of water quality and wetlands in the Grasslands; and
2. The Panoche-Silver Creek Coordinated Resource Management effort to address sediment and trace elements reaching the San Joaquin River from west-side tributaries.

The CNRF appreciates the invitation to support these projects, and we are pleased to provide our endorsement for the grant proposals. If a grant is offered for these projects, we can offer our services to accept and disburse grant funds, provide technical assistance in habitat evaluation or development work and in community outreach. We are particularly interested in opportunities to involve First Nation's people in habitat work, and Board member Mike Hammar, through his position with the Rural Indian Health Services, has links and contacts to make that happen.

You can contact me at (209) 358-9026. We look forward to helping carry out these projects.

Sincerely,

Ronn T. Slay

Ronn T. Slay, President,
California Natural Resource Foundation

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TELEPHONE (559) 582-9237
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April 13, 1999

COPY

Dr. Nigel W.T. Quinn
LAWRENCE BERKELEY NATIONAL LABORATORY
1 Cyclotron Road, 70A-3317K
Berkeley, CA 94720

SUBJECT: Grassland Area Farmers Support for CALFED Grant Proposals

Dear Dr. Quinn:

The Grassland Area Farmers have a long history of supporting innovative drainage reduction strategies on the west side of the San Joaquin Valley. As the proponent of the Grassland Bypass Project, the Grassland Area Farmers have invested millions of dollars in the past 3 years to improve monitoring and increase control over subsurface tile drainage leaving the area. Significant reductions in selenium loads contained in these discharges have been necessary to meet the strict selenium load limits imposed by the Project.

The CALFED proposal entitled "Real-Time Forecasting of Contaminant Loading from the Panoche/Silver Creek Watershed to the San Joaquin River" that you are submitting cooperatively with the Panoche/Silver Creek Coordinated Resource Management is of great interest to Grassland Area Farmers. Rainfall-runoff from the Panoche/Silver Creek watershed caused flooding of farmland during 1997 and 1998 and overwhelmed the resources of the drainage area to contain these flows. Accurate forecasting of flood flows will provide an early warning to the Grassland Area Farmers allowing more time for emergency response plans to deal with these flooding events. Successful completion of this study will be of great benefit to the Grassland Area Farmers in the Grassland watershed.

Sincerely,

Joseph C. McGahan

Joseph C. McGahan
Drainage Coordinator for the Grassland Area Farmers

JCM/p

REAL-TIME MANAGEMENT OF WATER QUALITY IN THE SAN JOAQUIN RIVER BASIN, CALIFORNIA

N. W. T. Quinn and J. Karkoski

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REAL-TIME MANAGEMENT OF WATER QUALITY IN THE SAN JOAQUIN RIVER BASIN, CALIFORNIA[1]

N. W. T. Quinn and J. Karkoski[2]

ABSTRACT: In the San Joaquin River Basin, California, a real-time water quality forecasting model was developed to help improve the management of saline agricultural and wetland drainage to meet water quality objectives. Predicted salt loads from the water quality forecasting model, SJRIODAY, were consistently within ± 11 percent of actual, within ± 14 percent for seven-day forecasts, and within ± 26 percent for 14-day forecasts for the 16-month trial period. When the 48 days dominated by rainfall/runoff events were eliminated from the data set, the error bar decreased to ± 9 percent for the model and ± 11 percent and ± 17 percent for the seven-day and 14-day forecasts, respectively. Constraints on the use of the model for salinity management on the San Joaquin River include the number of entities that control or influence water quality and the lack of a centralized authority to direct their activities. The lack of real-time monitoring sensors for other primary constituents of concern, such as selenium and boron, limits the application of the model to salinity at the present time. A case study describes wetland drainage releases scheduled to coincide with high river flows and significant river assimilative capacity for salt loads.
(KEY TERMS: water quality; real-time management; salts; drainage.)

INTRODUCTION

Real-time water quality management requires techniques that update the state of knowledge of a system continuously and allow actions to be taken to meet water quality objectives. Such techniques are being developed for the San Joaquin River Basin of California to promote voluntary compliance with state water quality objectives for priority pollutants such as selenium, boron, and total dissolved solids.

The techniques required to collect and transmit flow and stage data are well established. In California, public water agencies such as the Department of Water Resources (DWR), the U.S. Bureau of Reclamation (USBR) and the U.S. Geological Survey measure flow and stage routinely for a variety of applications. Only the California Data Exchange Center (CDEC), a department within the DWR, provides river stage and flood warning information on a real-time basis. The major clients of this system are local and state agencies concerned with flood management and the provision of emergency services. Agencies such as the US Army Corps of Engineers use this information to determine reservoir release schedules during high runoff periods. The real-time water quality management system under development for the San Joaquin River Basin takes advantage of some of the features of the existing hydrologic data acquisition and forecasting programs. Unique aspects of the real-time water quality management system that are not replicated by current programs are:

1. Use of water quality sensors: currently only EC, temperature, and pH are continuously logged, although a greater number of constituents of concern within California's river systems.
2. A continuous and integrated system of data error checking and validation because the data are used for regulatory purposes.
3. Addition of control systems that can be used to manage agricultural and wetland drainage water flow and water quality.
4. Institutions that coordinate actions and responses of regulators, operators, and other public and private entities.

[1]Paper No. 97053 of the *Journal of the American Water Resources Association*. **Discussions are open until August 1, 1999.**
[2]Respectively, Staff Geological Scientist, Lawrence Berkeley National Laboratory 70A-3317K, Berkeley, California 94720; and Environmental Engineer, U.S. Environmental Protection Agency, c/o State Water Resources Control Board, 901 P Street, Sacramento, California 95814 (E-Mail/Quinn: nquinn@mp405a.mp.usbr.gov).

BACKGROUND

The San Joaquin River drains a basin of approximately 34,560 square kilometers. Runoff from the basin is dominated by snowmelt and rainfall from the Sierra Nevada Range and its foothills to the east of the San Joaquin River. The three east-side tributaries, the Merced River, the Tuolumne River, and the Stanislaus River, provide the majority of the flow in the San Joaquin River (Figure 1). The predominant land use in the San Joaquin River Basin is irrigated agriculture. Irrigated agriculture on the west side of the Basin is supplied predominantly by imported water from the Sacramento-San Joaquin Delta, whereas the east-side tributaries and ground water provide the majority of the water supply to the east side of the Basin.

From a water quality point of view, the discharges from the Grasslands Basin are of particular interest. The Grasslands Basin is a hydrologic unit situated west of the San Joaquin River, bounded by Westlands Water District to the south and State Highway 140 to the north, that naturally drains to the San Joaquin River. The soils in the Grasslands Basin are naturally high in salts and of low permeability. The low permeability combined with the importation of water has resulted in a shallow groundwater table. To maintain productivity, the installation of artificial drainage is necessary in low-lying agricultural areas. Drainage produced from a 41,000 hectare agricultural area in the southern part of the Grasslands Basin [hereafter referred to as the Drainage Study Area (DSA)] contains high concentrations of certain trace elements and soluble salts that are harmful to fish and wildlife. The primary constituents of concern are salt, boron, and selenium.

In addition to discharges from the DSA, surrounding wetland areas also contribute a significant salt

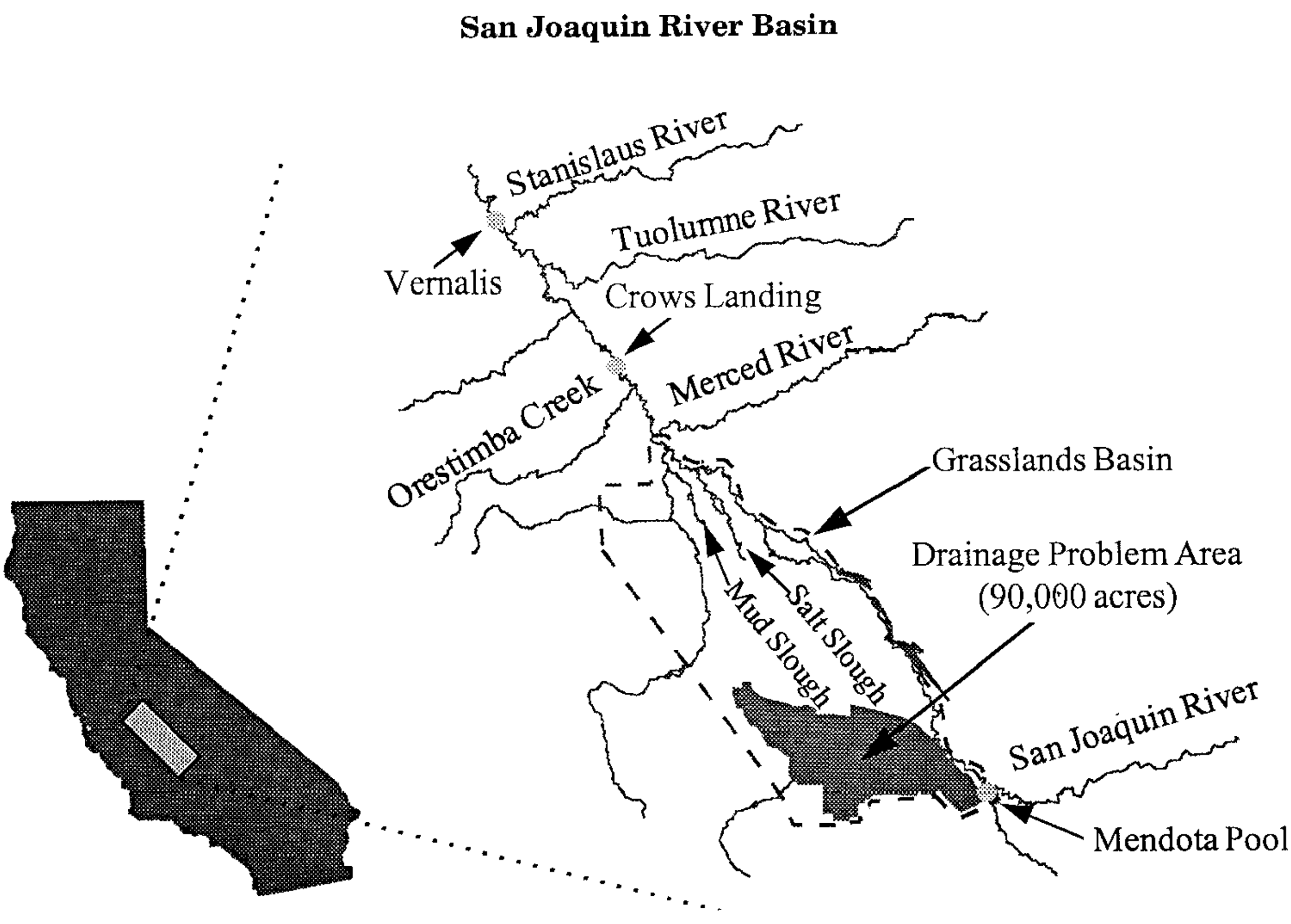

Figure 1. The San Joaquin River Basin Showing the Outline of the Grasslands Basins and the 41,000 Hectare Drainage Problem Area (DSA).

load to the San Joaquin River during the spring months (Grober *et al.*, 1995). The combined discharges from the agricultural lands and wetlands is conveyed through a system of canals and natural streams to the San Joaquin River. Figure 2 shows that the salt load contribution to the River from Mud and Salt Sloughs, which contain return flows from both agricultural and wetland areas in the Grasslands Basin, is high relative to other tributary sources of salt in the San Joaquin River Basin. Dilution of the poor quality discharges from the Grasslands Basin is provided by the east-side tributaries. Flows in the east-side tributaries are regulated to a large degree by upstream reservoirs which, in turn, are operated according to predetermined rules and release schedules. These rules and release schedules account for flood storage, fish migration, irrigation, hydropower, water quality control, and recreation.

In contrast to the high degree of regulation and control of east-side tributary flows, the discharge of pollutants from the DSA has historically been unregulated and uncontrolled. Sump pumps associated with subsurface agricultural drainage systems are designed to turn on automatically when water reaches a set level in the sump. Hence, the pattern of discharges from agricultural lands generally mirrors the irrigation season. In contrast, surface drainage discharge from seasonal wetlands occurs in early spring between February and April. Some control of the scheduling of the seasonal wetland drainage can be exercised by wetland managers, although these schedules are determined to a large extent by habitat requirements and local management preferences of privately owned duck clubs.

The timing of the discharges of dissolved solids and trace elements from the DSA and the timing of reservoir releases are such that the assimilative capacity of the San Joaquin River is often exceeded at the compliance monitoring locations. Opportunities have been identified for adjusting the timing of discharges and reservoir releases (A. Hildebrand, 1989, Letter sent to Ed Imhoff, Program Manager, San Joaquin Valley Drainage Program (1985-1990), Sacramento, California). The practical constraints to making such

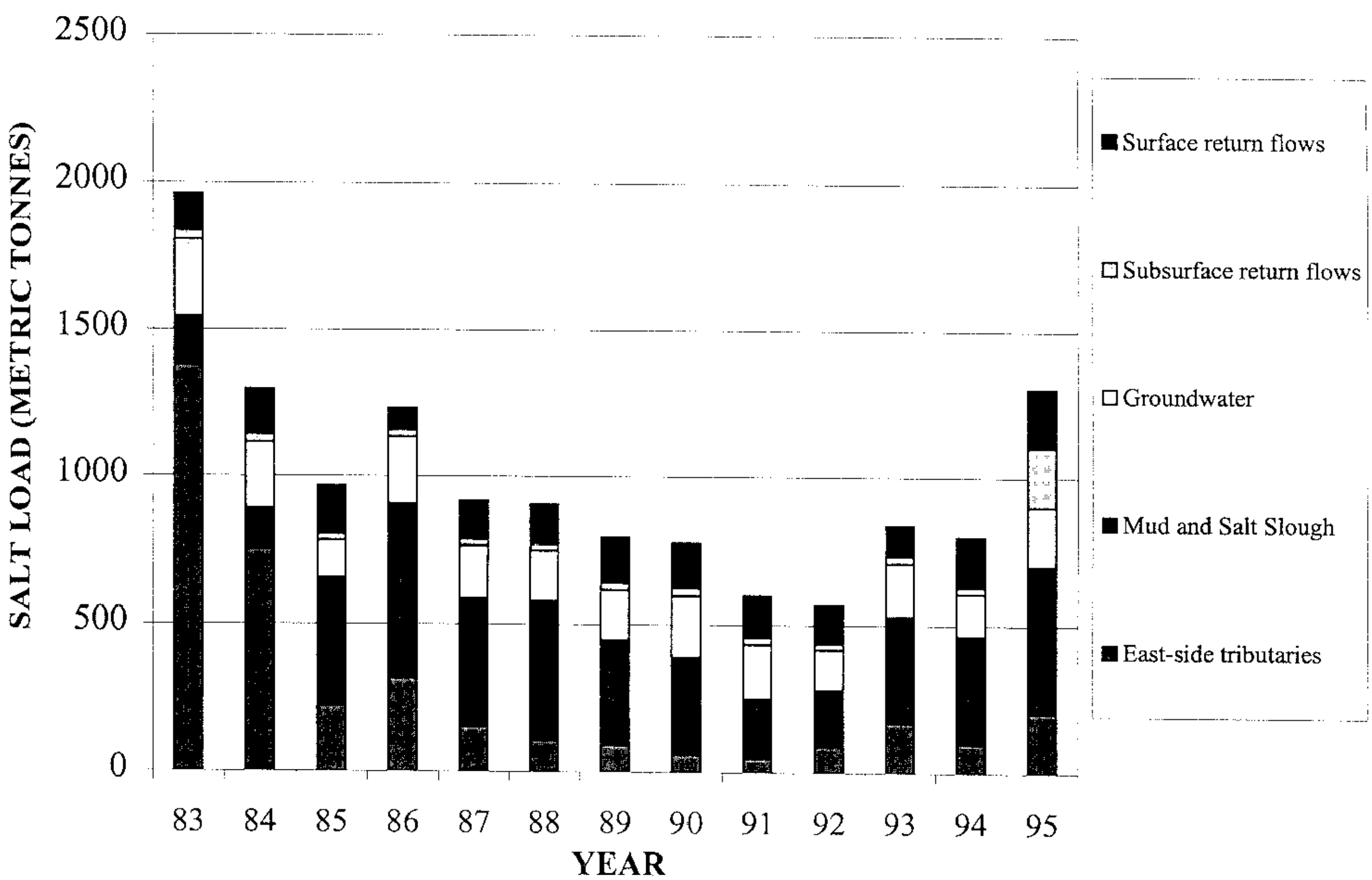

Figure 2. Salt Loading to the San Joaquin River From Various Sources.

adjustments have not been thoroughly explored (Karkoski *et al.*, 1995a). By making such adjustments, temporal variations in water quality can be minimized, and the frequency of violation of water quality objectives can be reduced. A real-time water quality management system, along with pollutant load reduction, could allow continued discharge of salt from agricultural lands and wetlands while minimizing the impacts on the San Joaquin River and eliminating violations of water quality objectives.

REAL-TIME WATER QUALITY MODELING IN THE GRASSLANDS BASIN

Previous real-time water quality modeling efforts in the Grasslands Basin have mostly focused on screening-level assessments of operational constraints on, and opportunities for, agricultural drainage discharges. The U.S. Bureau of Reclamation (USBR) developed a sophisticated planning model that considered several alternatives to meet selenium and boron water quality objectives in the San Joaquin River (Quinn, 1993; Quinn and Delamore, 1994). The alternatives considered were irrigation improvements, drainage water reuse, land retirement, and the use of holding reservoirs to regulate the release of drainage to the River. These alternatives were optimized to minimize the size of the regulating reservoirs and to ensure that the constraining water quality objective (selenium or boron) was not exceeded. The results of the modeling analysis suggested that with investments in drainage recycling facilities and the construction of regulating reservoirs with a total capacity of 4.3 million cubic meters, water quality objectives could be met at all times (USBR, 1991). The USBR model assumed perfect forecast and response to receiving water assimilative capacity and that the water quality of irrigation water and groundwater pumpage remained constant during the simulation period.

Another screening-level model developed by the Central Valley Regional Water Quality Control Board (CVRWQCB) (J. Karkoski, 1995 unpublished analysis) considered the effects of load reductions and model and response errors on the sizing of regulating reservoirs. Model and response errors were expressed by allowing only 80 percent of the available assimilative capacity to be used. When evaporation effects were considered, the storage size required for regulating reservoirs was found to be 26.8 million cubic meters. The large difference in regulating reservoir volume (4.3 vs. 26.8 million cubic meters) is a function of the different assumptions made in the two modeling approaches. In the case of the USBR model, the full assimilative capacity of the river was available and no annual selenium load cap was imposed; whereas the CRWQCB model assumed suboptimal use of the assimilative capacity and imposed the CRWQCB Basin Plan's annual selenium discharge load cap of 3,624 kg (CVRWQCB, 1996). The CRWQCB model also assumed that a mean annual discharge of selenium from the agricultural water districts to the San Joaquin river was 2,945 kg. Although the above models differed in certain assumptions, the premise shared by both models was that regulating reservoirs could be constructed and managed to respond to real-time conditions in the San Joaquin River.

In contrast, the analysis used by the CVRWCB in developing its control plan for selenium was based on a modified EPA load setting methodology (Karkoski *et al.*, 1995b; CVRWQCB, 1994) which assumes extremely limited ability to forecast, and therefore respond to, available assimilative capacity. The monthly flow record (1970-1991) was divided into eight flow regimes which differed based on water year type (dry and wet) and season. The selenium effluent limits were set for the low flow conditions in each flow regime (quasi-steady state) to meet an "allowable" rate of violation – once every three years as allowed by federal regulation.

Table 1 compares the annual allowable selenium load from the CVRWQCB analysis for dry years and wet years, under dynamic (real-time) versus quasi-steady state modeling assumptions. It is clear from Table 1 that the advantages of using a real-time system are significant to the discharger allowing a greater selenium load to be discharged, annually, without violating selenium concentration objectives.

TABLE 1. Comparison of Real-Time and Quasi-Static Selenium Load Limits.

	Wet Year Se Load (kg)	Dry Year Se Load (kg)
Quasi-Static	1405	455
Dynamic (Real-Time)	3364	2105

Operations Models

Although the screening level models point to potential advantages of adopting a real-time water quality management system, the actual opportunities presented by such a system can only be evaluated with the development of an operations model. An operations model is inherently more data-intensive than a screening or planning model.

The literature contains many examples of water related problems that have been addressed fully or in part through real-time data acquisition, information dissemination and operational control. Much of the literature describes the general field of optimization, dynamic programming, and optimal control theory. The efforts of these researchers highlight some of the challenges and potential solutions in the development of a real-time water quality management system for the San Joaquin River.

Krajewski *et al.* (1993) considered the real-time optimal control of power plant cooling water discharges. The effect of a single major discharge (power plant cooling water return flow) was simulated, along with ambient hydrometeorological conditions to determine compliance with the temperature standard 20 km downstream. A thermal model was used in conjunction with an optimization model; the optimization model minimized losses when the power plant was unable to generate power at a potential level and imposed penalties for violating the temperature standard. The loss function was stochastic in nature since it was dependent on the thermal model – the thermal model forecasted hydrometeorological conditions based on assumptions of initial and boundary conditions. Krajewski *et al.* (1993) were able to determine the effect of errors in forecasted hydrometeorological conditions on model error and the calculated net benefit.

Novotny *et al.* (1992) investigated the challenges of applying a real-time management and control system to wastewater treatment plants. Treatment plants are often designed based on assumptions of steady-state concentrations of influent to the treatment plant and effluent concentrations from the plant equal to allowable water quality standards. Novotny *et al.* (1992) suggested that a treatment process control and management scheme be adaptive, predictive, and efficient. Such a management model should be able to adapt to variations in input, able to forecast input changes, and be efficient by limiting idleness of plant units and the discharge of untreated waste. Storage was suggested by Novotny *et al.* (1992) as a buffer against temporal variations in assimilative capacity of the receiving water. Model features included an assessment of treatment plant output to the environment, response of the environment to the output and optimization of the system to maximize efficiency.

Krajewski *et al.* (1993) demonstrated that model errors due to lack of information on hydrodynamic parameters such as channel geometry, poorly understood processes such as ground water inflow, and lack of input data such as wetland and agricultural return flows can have a significant impact on the benefits realized from a real-time water quality management system. Novotny *et al.* (1992) suggested that a recursive parameter estimation method for autoregressive moving average models or a neural network model would provide the desirable features of adaptability and predictability required for real-time control of wastewater treatment processes. The need for these features is heightened when the size and variability of the system to be modeled increases (i.e., when the forecast lead times and model errors increase).

Although the general problems of data reliability are common to most of the real-time applications discussed in the literature, most appeared relatively tractable compared to the water quality management problem in the San Joaquin River Basin.

REAL-TIME DATA ACQUISITION SYSTEM

Although river stage, EC and temperature have been monitored on a real-time basis, other real-time water quality monitoring is generally limited to those properties and constituents such as temperature, pH, or dissolved oxygen for which no sample preparation is required. Techniques for the real-time measurement of other parameters of interest in the San Joaquin River, such as selenium and boron, have not been established nor are reliable sensors available.

A real-time water quality monitoring network has been established in the Grasslands Basin and along the main stem of the San Joaquin River. Nine sites were chosen for real-time monitoring of flow, electrical conductivity and temperature along the San Joaquin River and its tributaries. These monitoring sites are listed in order from upstream to downstream, together with the sensor data collected at each site:

- San Joaquin River at Lander Avenue (EC, flow, temp)
- Salt Slough at Highway 165 Bridge (EC, flow, temp)
- Grasslands Bypass (compliance point – site B) (EC, flow, temp)
- Mud Slough near Gustine (EC, flow, temp)
- Merced River near Stevinson (EC, flow, temp)
- San Joaquin River at Newman (flow)
- Orestimba Creek (EC, flow)
- San Joaquin River at Crows Landing (EC, flow, temp)
- San Joaquin River at Vernalis (EC, flow, temp)

The locations of these stations are shown in Figure 3. The data from these stations is currently telemetered via modem to central data processing stations in the USBR and the DWR, where the information is

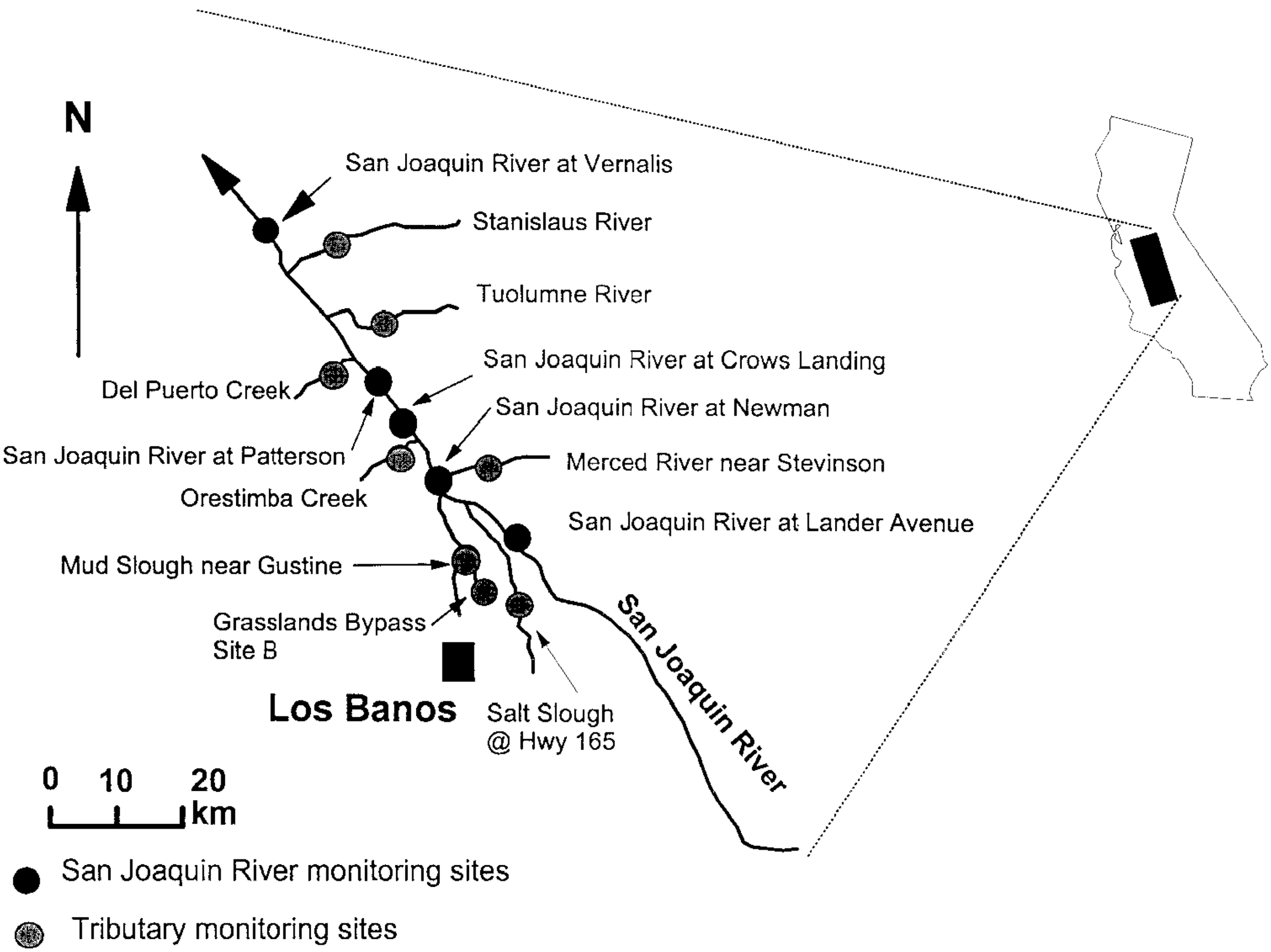

Figure 3. Location of Real-Time Monitoring Sites in the San Joaquin River Basin.

checked for errors and missing values and parsed into a format accessible by a daily water quality forecasting model. The evolution of this model and its application is the nexus of water resources modeling activities in four agencies within California: the State Water Resources Control Board, the U.S. Bureau of Reclamation, the California Department of Water Resources, and the California Regional Water Quality Control Board (Kipps *et al.*, 1997).

SAN JOAQUIN RIVER DAILY INPUT-OUTPUT MODEL

The San Joaquin River Daily Input-Output (SJRIO) model is a mass balance model which calculates daily flows and concentrations of total dissolved solids (TDS), boron, and selenium for a 96 km reach of the San Joaquin River from Lander Avenue to Vernalis (SWRCB, 1985). An extensive database was assembled, with data for water years 1977 to 1985, to run the model. The SJRIO was modified to accept stochastic data, so that it could be run with historical data, stochastic data, or a combination of both. The model has been further modified to run on a daily time step so that it can be used with real-time flow and water quality data on the SJR.

The daily model, SJRIODAY, contains the following tributary river segments:

- 10 km of Salt Slough below the Highway 165 gaging station
- 15 km of Mud Slough below the Gustine gaging station

- 8 km of the Merced River below the Stevinson gaging station
- 24 km of the Tuolumne River below the Modesto gaging station
- 14 km of the Stanislaus River below the Ripon gaging station
- Several kilometers of three west-side tributaries: Del Puerto, Orestimba and Hospital/Ingram Creeks

Daily flow calculations for the SJRIODAY model are made using hydrologic routing techniques. Water quality constituents are considered conservative. Those data are used to establish initial conditions for model runs and to generate a two-week forecast of flow and EC. In the absence of real-time data, boron and selenium forecasts are made using the most recently available data combined with historical means and the best judgment of the modeler. Real-time or forecasted rainfall can be used to account for additional runoff in the basin. Real-time data are supplemented by mean monthly flow and water quality data for other model components for which no real-time data are available, including: groundwater, riparian and appropriative diversions, surface and subsurface agricultural return flows, riparian evapotranspiration, evaporation, and precipitation. These components are estimated within the model based on seasonal variability and wet/dry water year classification provided by the modeler.

GRAPHICAL USER INTERFACE

A Graphical User Interface (GUI) was designed for the SJRIODAY model to be user friendly by exploiting the point-and-click capability of the Windows system (Figure 4). Upon execution of the GUI a colorful map of the San Joaquin River system is displayed on the computer screen. The user can direct the arrow cursor to any part of the map and, using the point-and-click system available within Windows, recall the data for review or for changes of input conditions. The user can also scroll through a display of dates, viewing the temporal variations of water quality parameters at any map location on the screen and can display spatial color coded changes in water quality at any given time. By clicking at a time advance button, the user can create a near-animation of salt movement through the San Joaquin River between Lander Avenue and Vernalis.

The GUI performs five functions:

1. Retrieves real-time monitoring data for initial conditions by modem from a dedicated computer or web site. (Telemetered data updated weekly by field staff after quality assurance checks have been performed.)
2. Edits and uploads water operators' operational schedules.
3. Runs the predictive SJRIODAY model.
4. Downloads model results.
5. Displays the results.

There are two versions of the GUI. The general version for water operators can edit and upload operational schedules of reservoir releases, download the results of computer runs using the forecasting model, and display the output from these runs. This version does not allow the user to make a full model run. The full version of the GUI has the same capabilities as the operators' version but also allows the user to download monitoring data and to run the forecasting model, SJRIODAY.

MODEL RESULTS AND FORECASTS

Forecasts of flow and water quality at Vernalis were made each week from February 12, 1996, to June 30, 1997, and a post audit of forecast accuracy was broadcast on the electronic listserver, comparing the forecasts with observations obtained from CDEC and the real-time monitoring system (Kipps *et al.*, 1997). Figures 5 and 6 show the performance of the forecasting model for predicting flow and EC at Vernalis. The observed CDEC and model-simulated flows at Vernalis and the observed CDEC and simulated TDS concentrations and assimilative capacities are in closer agreement in the case of the 1-week forecast than for the two-week forecast, as expected. The model performed well during most of 1996 and, in particular, the summer months, when flows and water quality on the San Joaquin River were dominated by agricultural drainage from Mud and Salt Sloughs. Predicted salt loads from the water quality forecasting model, SJRIODAY, were consistently within ± 11 percent of actual, within ± 14 percent for seven-day forecasts and within ± 26 percent for 14-day forecasts for the 16-month trial period. In general, the model tends to overestimate flow as well as EC.

The San Joaquin Valley was subjected to a series of severe winter storms between December 25, 1996,

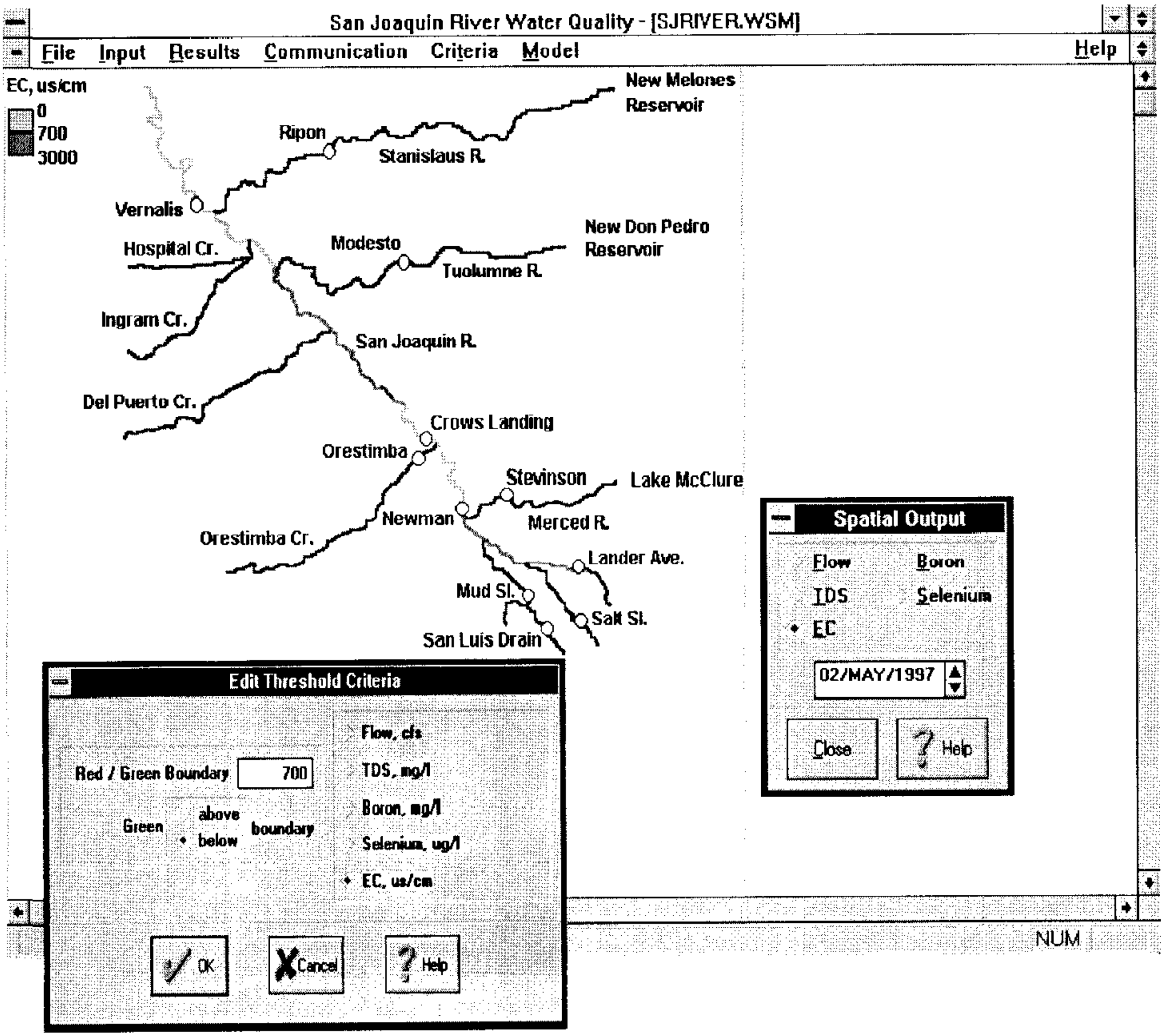

Figure 4. Graphical User Interface for the SJRIODAY Flow and EC Forecasting Model. The model can also access historical water quality data for selenium and boron. The EC criterion (entered as TDS) is user defined and produces a red coloration along the main stem of the San Joaquin when objectives are exceeded and a green coloration when water quality objectives are being met.

and January 25, 1997, which produced an extraordinary volume of runoff from the eastside Sierran watersheds. Without an accurate watershed model, runoff forecasts were based on estimates of the flood hydrograph from each contributing watershed and real-time flow data. When flow and EC for the 48 days dominated by rainfall/runoff events during the trial period were eliminated from the data set, the error bar decreased to ± 9 percent for the model, and ± 11 percent and ± 17 percent for the seven-day, and 14-day forecasts respectively. R-squared values for the model, seven-day and 14-day forecasts were 0.93, 0.88, and 0.76 using the full data set, which improved to 0.95, 0.91, and 0.79 when the 48 days dominated by rainfall-runoff events were eliminated.

Figures 5 and 6 illustrate the problems encountered in making accurate flow forecasts during the trial period. Although the model and the runoff forecasts continued to overestimate real-time flows between January 14 and January 25, 1997, levee breaks along the San Joaquin River accounted for some of the discrepancy. In some instances, the model

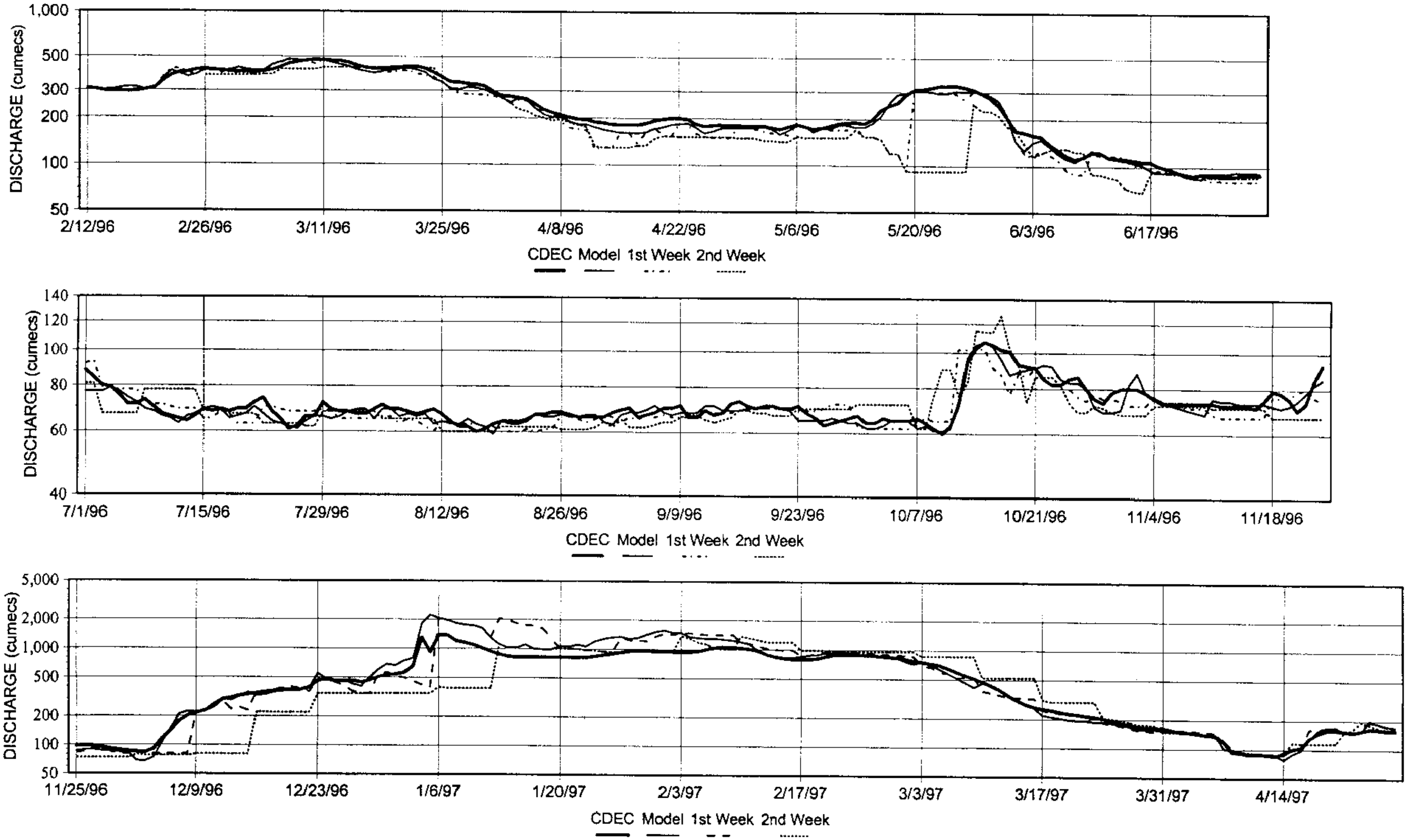

Figure 5. Comparison of Observed Vernalis Discharge Data from CDEC with Model Predictions and with One and Two Week Forecasts (February 1996 to April 1997).

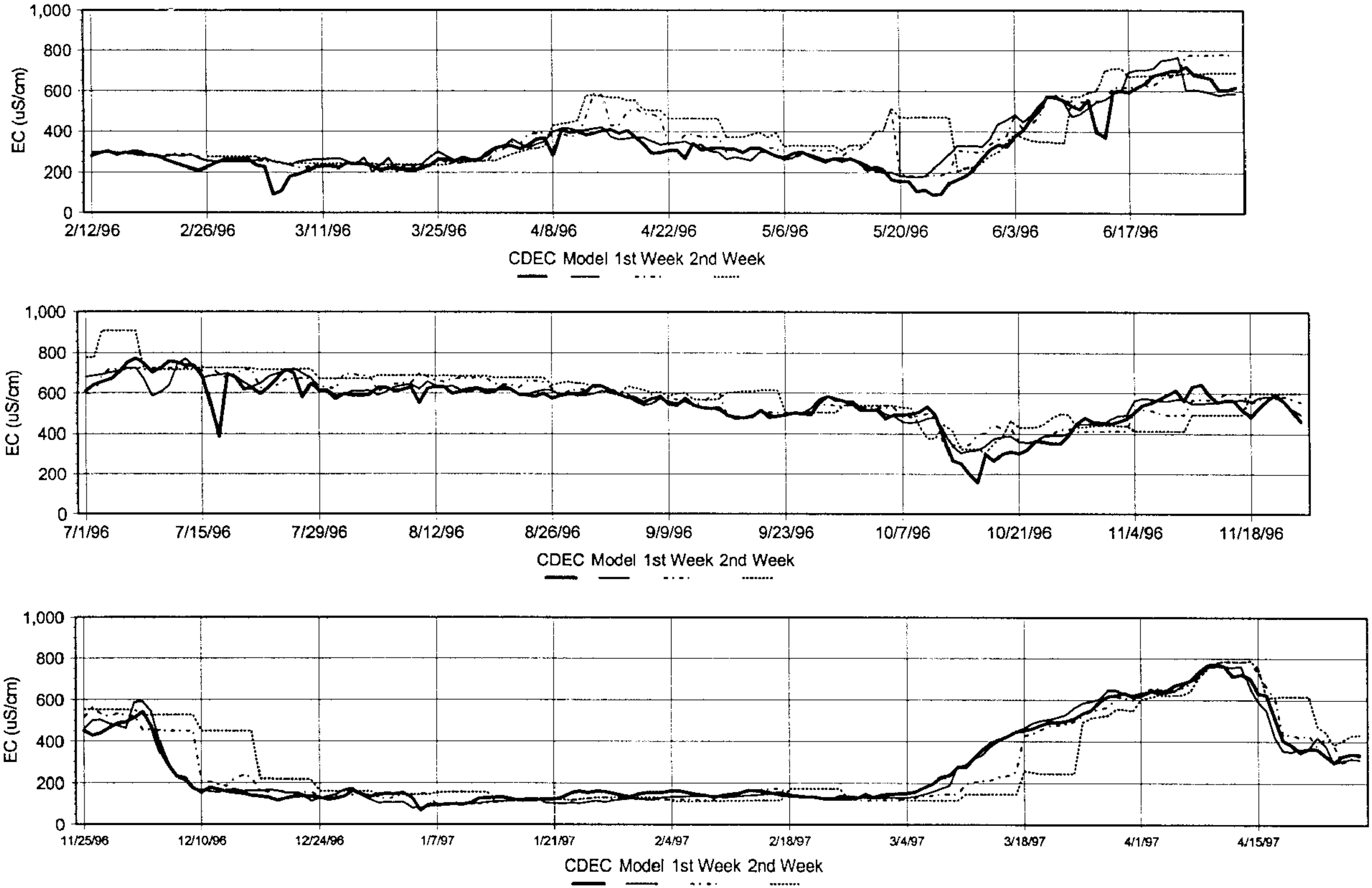

Figure 6. Comparison of Observed Vernalis Electrical Conductivity (EC) Data from CDEC with Model Predictions and with One and Two Week Forecasts (February 1996 to April 1997).

and forecasts alerted the analysts to problems in the monitoring networks, which included the failure of an EC sensor and a flooding problem when a portion of the river flow was diverted around the gaging station. The dominance of east-side tributary flows on San Joaquin River water quality during the trial period improved the accuracy of prediction. Model and forecast EC concentrations were not significantly different from the real-time EC data.

REAL-TIME MANAGEMENT OF FLOW AND WATER QUALITY

The accuracy of the forecasts performed with the aid of the model is greatest when schedules of east-side reservoir releases and estimates of agricultural and wetland drainage discharges are available. These deterministic inputs reduce the errors associated with the inherently stochastic nature of river flows and agricultural loads. Reliable forecasts and the capability of dischargers and diverters to act upon these forecasts requires information exchange and coordinated management.

REOPERATION OF EAST-SIDE RESERVOIRS

Water districts make releases from east-side reservoirs for power generation, irrigation, and municipal water to cities and towns located along the major San Joaquin tributaries. Reservoir operators are obligated to make releases to aid fish migration during certain times of the year pursuant to their FERC licenses and for recreation and other purposes negotiated with local interests. East-side reservoir operators have had few incentives in the past to cooperate with agricultural water districts and wetland refuge managers to improve water quality conditions in the San Joaquin River. These attitudes are shifting with recent legislation to encourage water transfers and water marketing. Such incentives have allowed the Federal Government to acquire water supplies for tributary pulse flows to aid fish migration. The U.S. Bureau of Reclamation has developed a scheme to compensate east-side water districts for additional scheduled releases that exceed normal operations for the purpose of improving the salmon fishery. These pulse flows provide windows of opportunity for west-side agricultural water districts and wetland managers to increase discharge flows and salt loads without violating the San Joaquin River salinity objectives at Vernalis.

WETLAND DRAINAGE MANAGEMENT

Wetland discharges of salt to the river have come under increased scrutiny ever since the provision of additional Federal water supply under the Central Valley Improvement Act of 1992. In the Grasslands Basin there are 41,000 hectares of wetlands – a combination of permanent, seasonal and upland habitat for migrating wildfowl of the Pacific Flyway. The greatest impact to the San Joaquin River is from seasonal wetlands which are usually flooded in the months of September and October and drain during the spring months of March, April and May. Approximately 10 percent of the salt in the San Joaquin River derived from these wetland discharges. The potential for real-time management of salts from these wetlands is constrained by the necessity to provide maximum food value and habitat requirements for different wildfowl species.

During early January 1996 the Grassland Water District, in cooperation with the Water Quality Committee of the San Joaquin River Management Program (SJRMP), conducted an experimental early drainage release of ponded water. This early release provided a potential benefit to the River by reducing the likelihood of downstream salinity impacts later in the season and reducing the risk of salinity objective violations. The Water District requested that the authors provide a forecast of the most advantageous time to make this release. A model forecast, made on January 15, 1996, suggested that the combination of high river flows and an imminent rainstorm might provide the necessary assimilative capacity. The peak wetland release was timed so that it would coincide with peak flow in the San Joaquin River. Wetland flushing began on January 18 and ended on February 19, with the peak flow occurring between January 27 and February 10. This peak flow arrived at Vernalis between February 1 and February 14 (Figure 7). On January 15, before the arrival of the wetland releases, flow at Vernalis was approximately 56 cubic meters per second, and the EC was 1000 uS/cm. At the time of arrival of the peak wetland releases at Vernalis, flow at Vernalis ranged from 148 to 294 cubic meters per second and the EC ranged from 220 to 430 uS/cm. Excess assimilative capacity was observed in the River throughout the simulation period as a result of the rainfall-runoff events in the upper watershed. No violations of the EC objective occurred during the trial period, and there were no EC violations in the San Joaquin River during March and April 1996.

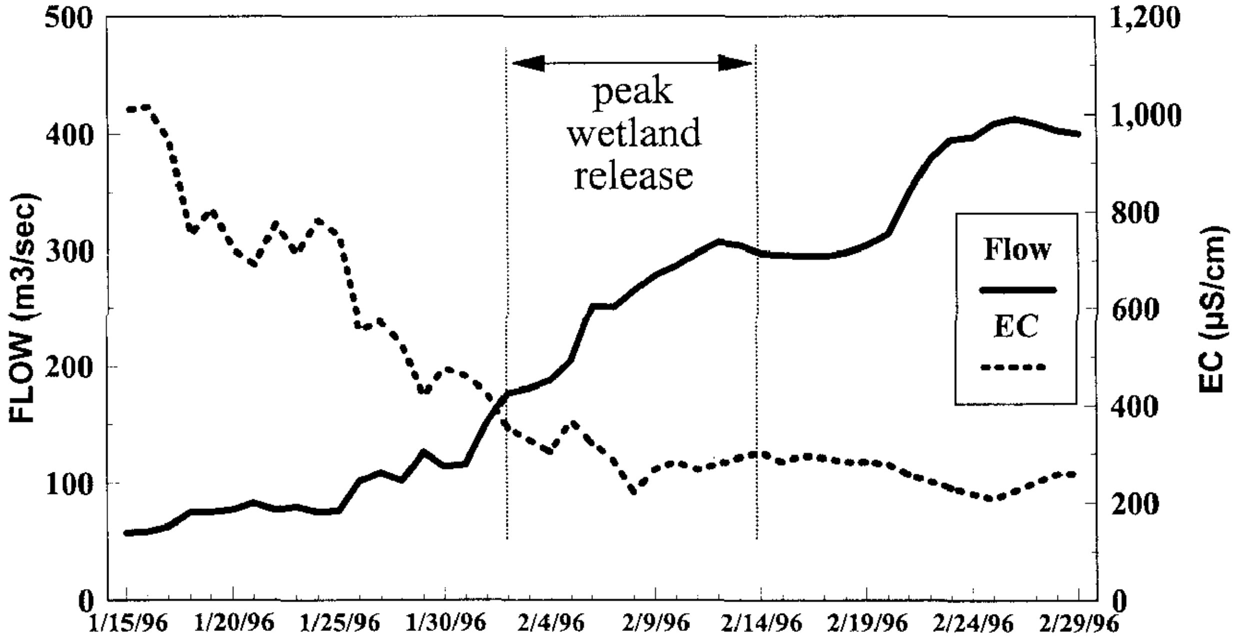

Figure 7. Flow and Electrical Conductivity (EC) in the San Joaquin River Near Vernalis.

MANAGEMENT AND CONTROL OF AGRICULTURAL DRAINAGE

The most cost-effective agricultural drainage control structures allow storage of drainage effluent during periods of low assimilative capacity and discharge of drainage effluent during periods of high assimilative capacity. Drainage effluent is currently managed by the following techniques: (a) drainage source control and water conservation practices; (b) minimization of tailwater and separation of tailwater and tilewater; (c) recirculation and blending of subsurface drainage water; and (d) manipulation of subsurface drainage sumps. Implementation of these techniques requires intensive water management and require careful monitoring of salts.

The Grasslands Bypass Project, initiated in October 1996, is a unique program under which the agricultural water districts agreed to limit monthly and annual selenium loads from the 41,000 hectare DSA. A fee schedule for all exceedences of monthly and annual targets (with a cap of $250,000) was agreed after negotiations between the farmers, agricultural water districts, and the state and federal agencies participating in the project. Although the stringent monthly load limits currently constrain the flexibility of the water districts to adjust discharges to match river assimilative capacity, actions have been taken that will lead to improvements in future real-time management of discharges. A multi-million dollar investment by the participating water districts in flow and EC monitoring systems, recirculation pumps and ditches, drainage storage facilities and sump control systems will allow centralized control of drainage discharges from each district outlet.

Source Control and Water Conservation

Water conservation practices have improved in each of the DSA water districts through the use of irrigation consultants, the implementation of tiered water pricing policies, and the organization of water management workshops for farm workers with instruction in both English and Spanish. Considerable improvements in on-farm irrigation practices have occurred over the last 12 months with investments in sprinkler systems and gated pipe to reduce losses associated with furrow pre-irrigation and conveyance in earth-lined ditches. Farmers in the DSA had found that irrigation efficiencies were poorest during pre-irrigation resulting from poor application uniformity.

Tailwater Return Systems

District policies that require all irrigation tailwater to be recycled and kept separate from subsurface drainage have improved on-farm irrigation efficiencies and reduced drainage volumes. One of the effects of implementing this policy has been to educate ditch tenders and increase their understanding of the effect of management practices on irrigation distribution uniformity. As a result many fields have been subdivided and furrow row lengths reduced from 800 meters (1/2 mile) to 400 meters (1/4 mile).

Drainage Recirculation

The volume of subsurface drainage that can be recirculated is limited by the tolerance of the crop to salt and boron concentrations. Generally, when subsurface drainage is recirculated, it is blended with good quality surface supplies to minimize potential negative impacts on crop yield. Ample supplies of good quality supply water are needed periodically in an irrigation system where recirculated subsurface drainage is used (Rhoades,1984).

Manipulation of Drainage Sumps

Drainage sump pumps are typically activated when the water level rises above an electronic sensor located in the sump. The pump sensors would be overridden so as to shut off during periods of low river assimilative capacity and to turn on only when river assimilative capacity was adequate to accommodate drain flows. The manipulation of sump pumps has limited utility during periods of available assimilative capacity, i.e., during fall and winter months and in "wet" water years.

Regulating Reservoirs

One means of reducing the response time is to build regulating reservoirs, such as those considered in the planning studies, discussed earlier. During periods of low assimilative capacity, excess drainage is stored in the reservoir and later released when assimilative capacity becomes available. If these reservoirs were to be located close to the San Joaquin River storage could be manipulated to take advantage of short-term periods of high assimilative capacity. The experience at Kesterson Reservoir (Presser, 1994) and in the evaporation ponds of the Tulare Basin, California (Skorupa and Ohlendorf, 1991) have shown the potential danger of holding large volumes of selenium contaminated water above ground for extended periods of time. In both cases, bioaccumulation resulted in observable impacts to wildlife, even at low water column concentrations. Research and monitoring studies are needed to determine safe holding times in these reservoirs. These reservoirs should also be designed to minimize their attraction to wildlife by making them deep with steep shorelines, denuded of vegetation.

INSTITUTIONAL FRAMEWORK

For the real-time water quality management system to be fully implemented and successfully used by stakeholders, some institution building and reform at the state level will likely be required. Incentives need to be created for all parties for the acquisition, use and sharing of drainage and reservoir release data. Developing systems for dissemination of current information to interested parties is the first step and has been initiated through use of the Internet and the creation of an e-mail listserver for the project. The listserver automatically relays messages (including forecasts of real-time flow, water quality and scheduled reservoir release data) for downstream fisheries, flood control and recreation to the entire multiagency subscriber list.

A problem is created in this unstructured sharing of information in that it does not have a formal feedback loop – hence actions taken as a result of the flow and water quality forecasts gleaned from the listserver are not accounted for in the current system. For example, a downstream riparian diverter might increase pumping above typical seasonal levels from the San Joaquin River, if forecasts indicated a short term improvement in water quality. This action would decrease flow and salt load in the San Joaquin River reducing the accuracy of the Vernalis forecast. Forecasted Vernalis EC could increase or decrease depending on the location of the diversion and the relative salt concentration of the river relative to the Vernalis EC objective. One means of dealing with the feedback problem would be to set up specific schedules for issuing San Joaquin River water quality forecasts, and for issuing official updates to these forecasts, based on feedback information. To do this effectively will require the establishment of a central authority with responsibility for water quality in the San Joaquin River with control over drainage and reservoir operations. The current system has been in place for less than two years. It is envisaged that the technology transfer process and the loosening of institutional constraints will take several more years before the potential benefits of this system are realized. A research and development grant of $900,000 has been awarded to the SJRMP Water Quality Committee to continue development of the real-time water quality forecasting system over the next three years.

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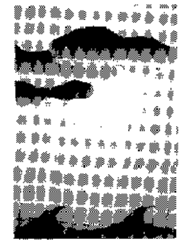
Numerical Prediction of Precipitation and River Flow over the Russian River Watershed during the January 1995 California Storms



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ABSTRACT

Precipitation and river flow during a January 1995 flood event over the Russian River watershed in the northern Coastal Range of California were simulated using the University of California Lawrence Livermore National Laboratory's Coupled Atmosphere–River Flow Simulation (CARS) System. The CARS System unidirectionally links a primitive equation atmospheric mesoscale model to a physically based, fully distributed hydrologic model by employing an automated land analysis system. Using twice-daily National Meteorological Center eta model initial data to provide the large-scale forcing to the mesoscale model, the CARS System has closely simulated the observed river flow during the flooding stage, where the simulated river flow was within 10% of the observed river flow at the Hopland gauge station on the Russian River.

1. Introduction

Predicting local precipitation, land surface hydrology, and river flow is important for early flood warnings and for efficient management of reservoirs. In mountainous areas such as the western United States, steep terrain and narrow valleys can cause severe flooding during heavy precipitation events. To prevent flooding, local reservoirs need to release stored water when heavy precipitation is expected. Therefore, inaccurate predictions of local precipitation and river flow can cause either unexpected flooding or unnecessary releases of water resources.

As part of an effort to investigate regional-scale atmospheric flows, precipitation, surface hydrology, and river flow at various temporal scales, we have developed a Coupled Atmosphere–River Flow Simulation (CARS) System. This modeling system can be used to forecast or diagnose both atmospheric conditions and land surface hydrology on regional to catchment scales. We applied the CARS System to a preliminary numerical prediction study over the Russian River Basin in the northern California Coastal Range during a flooding period in early January 1995. The following sections discuss the CARS System and the simulated precipitation and river flow.

2. The Coupled Atmosphere–River Flow Simulation System

The CARS System consists of three unidirectionally coupled numerical models: 1) the Mesoscale Atmospheric Simulation (MAS) Model, 2) the Automated Land Analysis System (ALAS), and 3) a modified version of the hydrology model known as TOPMODEL. As illustrated in Fig. 1, the CARS System can be nested within either a large-scale forecast or analysis data. Hence, the CARS System may be employed for predictions of regional weather and river flow or for simulating regional climatology, depending on the choice of the large-scale input data.

The unidirectional coupling occurs as follows. The MAS model simulates precipitation and atmospheric variables at a 20-km horizontal resolution using initial and time-dependent lateral boundary conditions

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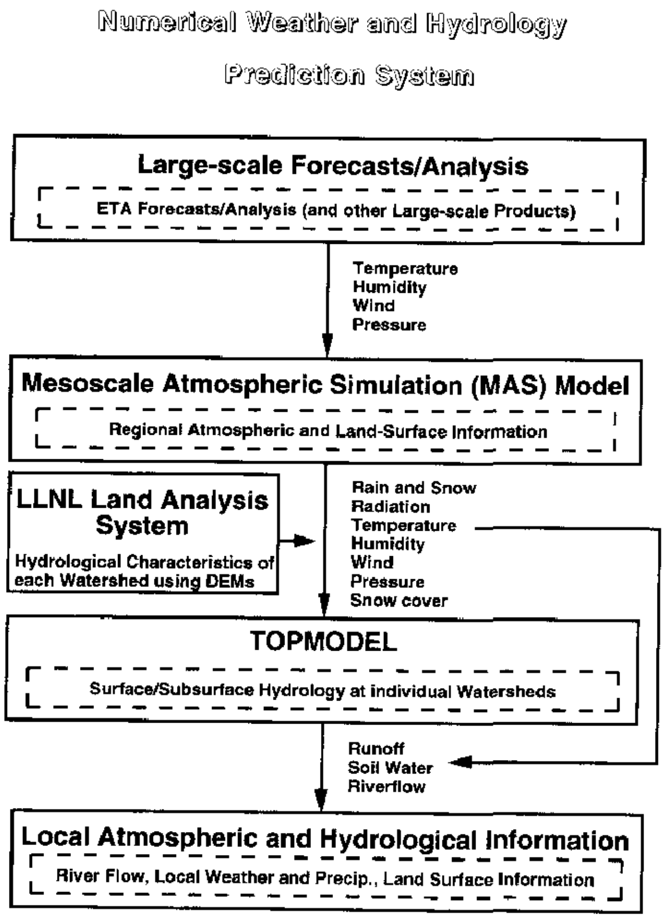

FIG. 1. Nesting procedure of the CARS System.

obtained from large-scale atmospheric input data. The simulated precipitation and atmospheric variables are then averaged over individual watershed areas computed by ALAS. TOPMODEL computes river flow using the watershed area mean precipitation and atmospheric variables simulated by MAS in conjunction with surface properties provided by ALAS.

The MAS model (Kim and Soong 1994) is a primitive equation, limited-area mesoscale model, which includes a third-order-accurate advection scheme (Takacs 1985) and physical processes for 1) precipitation and thermal forcing due to deep convective clouds and stratiform clouds, 2) solar and terrestrial radiative transfer within the atmosphere, and 3) turbulent transfer at the earth's surface and within the atmosphere. MAS directly computes rainfall and snowfall separately using a bulk cloud microphysics scheme by Cho et al. (1989). It also provides mixing ratios of cloud water and cloud ice that are used to determine optical properties of water- and ice-phase clouds for computing solar and terrestrial radiative transfer. Interactions between the atmosphere and land surface are computed using the Coupled Atmosphere–Plant-Snow Model (Mahrt and Pan 1984), which has been fully coupled to MAS and has enabled us to keep track of available water resources, including those stored in the snowpack.

The Automated Land Analysis System is based on software developed by the United States Geological Survey (Jenson and Dominque 1988) and the Lawrence Livermore National Laboratory (Miller 1995). ALAS provides information on topographic properties such as river networks, watershed areas, and hydrologic characteristics at specified resolutions using digital elevation model data. The area and location of watersheds determined by ALAS are matched to the grid points of the MAS model, so that computed watershed area mean atmospheric variables and precipitation are available to TOPMODEL as input.

TOPMODEL is a physically based, fully distributed hydrology model. The conceptual version of TOPMODEL was initiated by Kirkby (1975), and the numerical model was developed by Beven and Kirkby (1979). TOPMODEL computes the soil water budget, surface–subsurface flow, and the volume of routed river flow in a specified area. It has been improved to include the effects of spatial scale on hydrologic processes (Sivapalan et al. 1990; Beven et al. 1988; Wood et al. 1990) and has been applied to many surface hydrological studies, including the effects of terrain on streamflow (Beven and Wood 1983) and the effect of climate change on hydrological processes (Wolock and Hornberger 1991). Our version of TOPMODEL has been further modified in that it is driven by atmospheric variables (precipitation, temperature, winds, and radiation) provided by the MAS model.

3. Precipitation and river flow simulations over the Russian River Basin

During January 1995, California received an unusually large amount of precipitation. Between 7 and 11 January, three consecutive, strong storms hit California. Several parts of the state were affected by high water, as the soils became saturated when the second storm reached the area. The Russian River Basin was among the areas hardest hit with an estimated flood-related damage of over $800 million. We carried out a simulation of local precipitation and river flow during a flooding episode along the Russian River Basin in the northern California Coastal Range.

River flow simulations require separate inputs for rainfall and snowfall, since snowfall does not immediately affect river flows. The simulated 24-h accumulated rainfall and snowfall over the southwestern United States on 10 January 1995 are shown in Figs. 2a,b. The MAS model predicted heavy rainfall during this period along the northern Coastal Range, the western slope of the Sierra Nevada, and the southern California coast near Santa Barbara, which was also severely flooded. Rainfall to the north of the San Francisco Bay, including the northern part of the Russian River Basin, was particularly heavy. Since the snow line was located at approximately 2000 m (Fig. 2b), all of the precipitation that fell over the Russian River Basin was in the form of rain, which quickly saturated the soils and caused overland flooding.

Orographic features of the terrain in California cause strong spatial gradients in precipitation. To illustrate the importance of accurate estimations of local precipitation for computing river flows within mountainous terrain, we computed area mean daily precipitation over the entire Russian River Basin (3425 km^2) and over the area within the Russian River Basin north of the Hopland gauge station (658 km^2) during the simulation period. The terrain of the entire Russian River watershed and an enlargement for the region of the Russian River watershed north of the Hopland gauge station (hereafter Hopland watershed) are shown in Fig. 3. The simulated daily precipitation averaged over the entire Russian River watershed and the Hopland watershed frequently differs by a factor of 2–3, especially during the flooding stage (Fig. 4).

Figure 5 compares the simulated 6-h accumulated precipitation averaged over the Hopland watershed to the observed area mean precipitation, which is used to run the operational river flow model of the California–Nevada River Forecast Center. These observed area mean precipitation data are based on four rain gauge values from Willits, Ukiah, Yorkville, and Lake Mendocino (Fig. 3). A weighting function based on climatological rainfall distribution within the Hopland watershed (E. Strem 1995, personal communication) gives observed area-averaged precipitation of these areas as

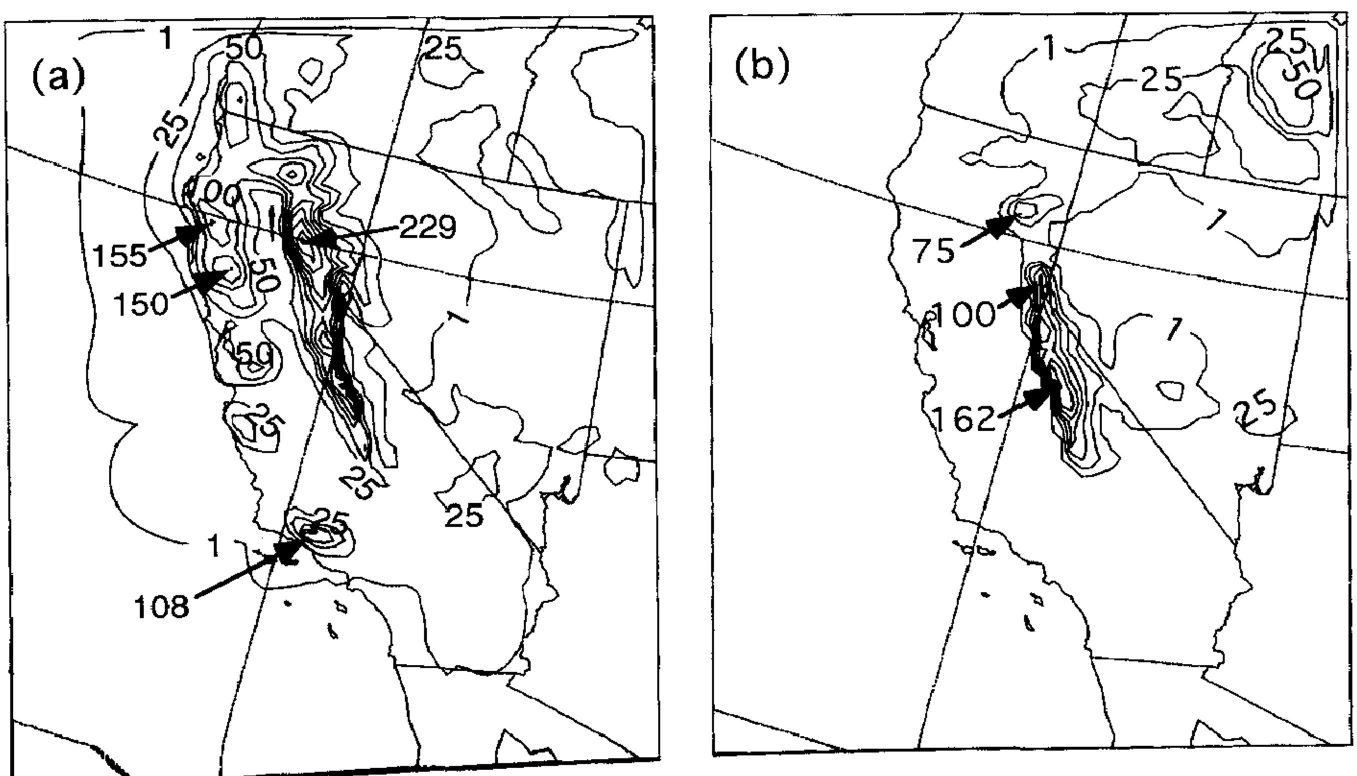

FIG. 2. A 24-h accumulated (a) rainfall and (b) snowfall, in equivalent water depth, forecasts for 0000 UTC 1 September–0000 UTC 1 October 1995 over the model domain. Units are in mm day^{-1}. The contour interval is 25 mm.

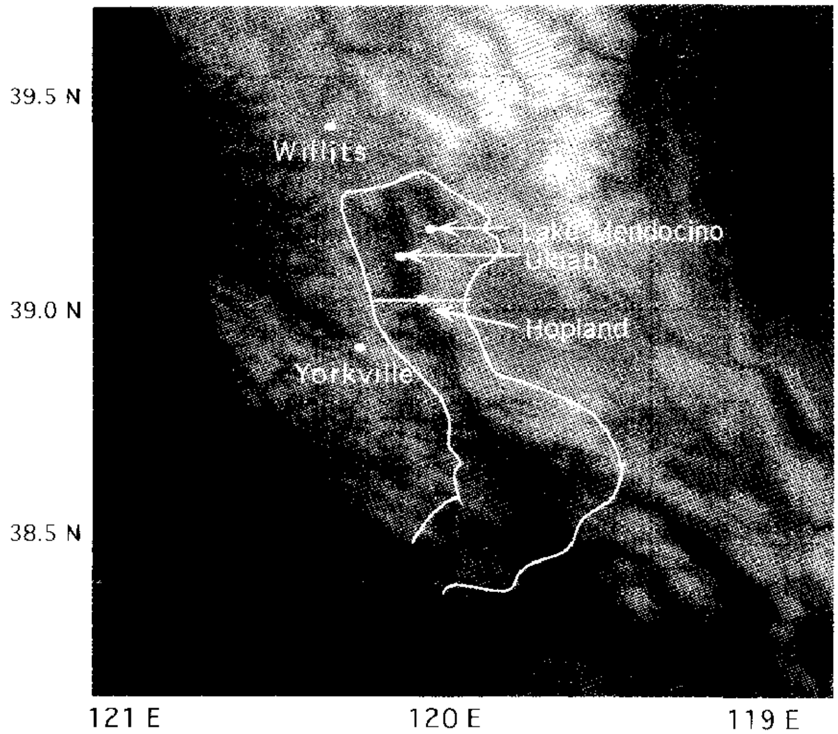

FIG. 3. Terrain and watershed boundary of the Russian River Basin at a 250-m resolution. The Hopland watershed is located north of the 39°N parallel (indicated by a solid east–west line at Hopland) within the Russian River Basin.

$$\bar{P}_{\text{Hopland}} = 0.22P_{\text{Willits}} + 0.28P_{\text{Ukiah}} + 0.23P_{\text{Yorkville}} + 0.28P_{\text{Lake Mendocino}},$$

where $\bar{P}$ and P are area mean and single rain gauge values, respectively. The simulation has well captured the amount and timing of precipitation over the Hopland watershed during the study period, except on 10 January where the model significantly overestimated the observed precipitation. This overestimation was due to a large amount of moisture influx into the area prescribed by the eta model initial fields.

In this study, soil texture, topography, and the initial soil water saturation deficit were the most important surface properties for computing river flow. The initial soil water content for this simulation was obtained by running TOPMODEL with the observed climate history prior to the January 1995 storms. Watershed properties for the Hopland Basin were computed at a 200-m resolution using topographic elevation data at a 100-m resolution, as sensitivity studies indicated that this resolution is sufficient for the region.

Figure 6 illustrates the observed and simulated daily mean river flow volume at the Hopland gauge station from 1 to 12 January 1995. The CARS System simulated the river flow rate within 10% accuracy during the flood stage. A significant overestimation of the modeled river flow for 11 January was due to overpredicted rainfall on 10 January. The simulated river flow exceeded the observed river flow by approximately 30% during low flow periods before flooding mainly due to the uncertainties in the initial soil water content.

4. Conclusions

We have developed a Coupled Atmosphere–River Flow Simulation System by coupling a mesoscale atmospheric model with a physically based, distributed hydrologic model that simulates regional precipitation, mesoscale atmospheric circulations, surface hydrology, and river flow. This prototype system successfully modeled the January 1995 storms that caused severe flooding along the Russian River watershed in the northern California Coastal Range. The simulated area mean precipitation is in strong agreement with the observed precipitation. The simulated river flow is also in strong agreement with the observed value at the Hopland gauge station along the Russian River, as the simu-

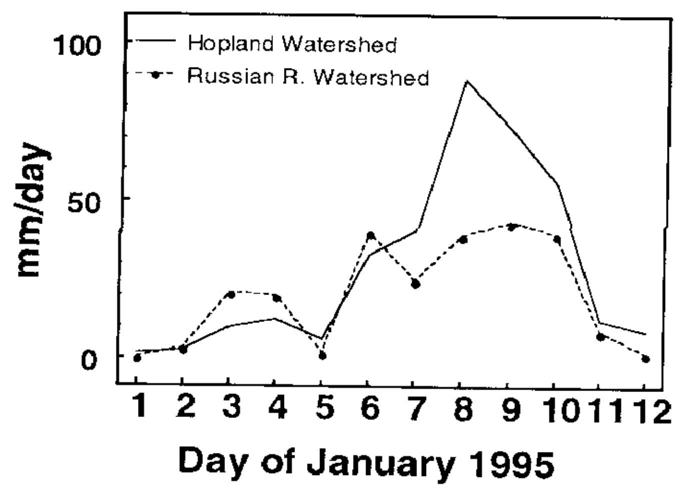

FIG. 4. The simulated area mean precipitation over the entire Russian River watershed (dashed line with solid circles) and over the Hopland watershed (solid line).

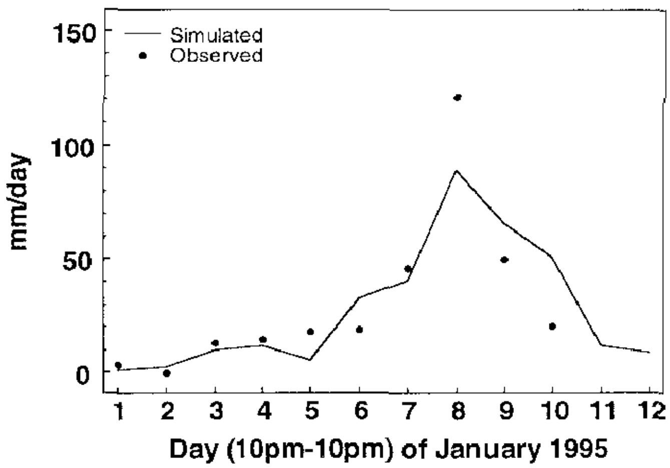

FIG. 5. The observed (circles) and simulated (line) area-averaged, 6-h accumulated precipitation over the Hopland watershed.

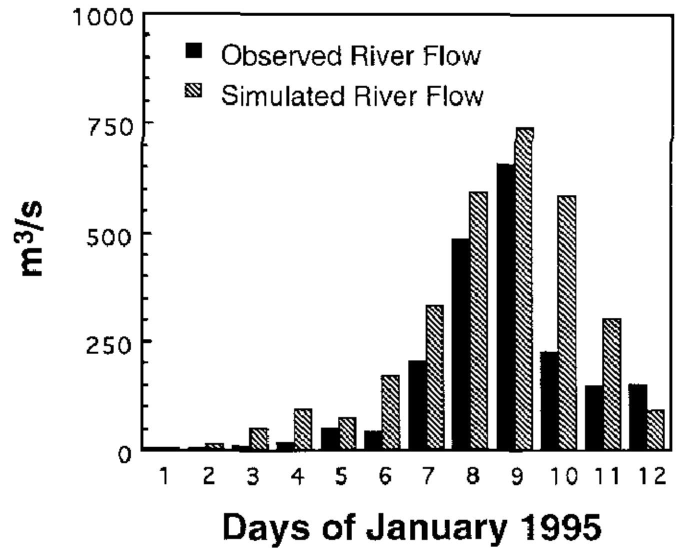

FIG. 6. The observed (solid bar) and simulated (shaded bar) river flow rate at the Hopland gauge station.

lated river flow during the flooding period differs from the observed value by 10%.

The CARS System is currently being employed for experimental numerical weather prediction for the southwestern United States. We have successfully run this system continuously from 1 January to 30 March with a similar accuracy level. These results are being prepared for a more detailed manuscript. The hydrologic simulation component of the CARS System is being extended to include several other major river systems within California, including the Lake Shasta inflow, the American River, and the Feather River.

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